

A SYSTEM FOR THE AUTOMATIC COMPUTATION OF CROSS-SECTIONS INCLUDING SUSY PARTICLES

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We introduce a new method to treat Majorana fermions on the GRACE system, which has already been developed for the computation of the matrix elements for the processes of the standard model. In the standard model, we already have included such particles as Dirac fermions, gauge bosons and scalar bosons in the system. On the other hand, there are four Majorana fermions called neutralinos in the minimal SUSY standard model (MSSM). In consequence, we have constructed a system for the automatic computation of cross-sections for the processes of the MSSM. It is remarkable that our system is also applicable for another model including Majorana fermions once the definition of the model file is given.

1. Introduction

The quest of new particles is one of the most important aim of the present high-energy physics. Though there are many theories which predict undiscovered particles, supersymmetric (SUSY) theories are fascinating ones because of the beautiful symmetry between bosons and fermions at the unification-energy scale. It, however, is a broken symmetry at the electroweak-energy scale. The relic of SUSY is expected to remain as a rich spectrum of SUSY particles, partners of usual matter fermions, gauge bosons and Higgs scalars, named sfermions, gauginos and higgsinos, respectively.¹

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Since there exist so many particles and their interactions, it is a skilled job to calculate the cross-sections for the processes with the final 3-body or more. We have already known within the standard model that the calculation of the helicity amplitudes is more advantageous to such a case than that of the traces for the gamma matrices with REDUCE.^{2,3} The program package CHANEL⁴ is one of the utilities for the numerical calculation of the helicity amplitudes.

It, however, is also hard work to construct a program with many subroutine calls of CHANEL by hand. Thus we need a more convenient way to carry out such a work. Several groups have started independently to develop computer systems which automate the perturbative calculation in the standard model with different methods.^{5–8} The GRACE system,⁵ which automatically generates the source code for CHANEL, is one of the solutions. The system also includes the interface and the library of CHANEL, and the multi-dimensional integration and event-generation package BASES/SPRING v5.1.⁹

In the SUSY models, there exist Majorana fermions as the neutral gauginos and higgsinos, which become the mixed states called neutralinos. Since anti-particles of Majorana fermions are themselves, there exists so-called ‘Majorana-flip’, the transition between particle and anti-particle. This has been the most important problem which we should solve when we realize the automatic system for computation of the SUSY processes.

In a recent work,^{10,11} we developed an algorithm to treat Majorana fermions in CHANEL. In the standard model, we already have such particles as Dirac fermions, gauge bosons and scalar bosons in the GRACE system. Thus we have constructed an automatic system for the computation of the SUSY processes by the algorithm above in the GRACE system.

2. Majorana fermions into new GRACE

The GRACE system in the public ftp-site is for the automatic computation of the cross-sections for the processes within the standard model.¹² The GRACE system has become more flexible for the extension in the new version called ‘**grc**’,¹³ which includes a new graph-generation package.¹⁴ With this package, every graph can be generated based on a user-defined model. It is necessary for us to make the library and the interface of CHANEL and the model file for including the SUSY particles.

The method of computation in the program package CHANEL is as follows:

1. To divide a helicity amplitude into vertex amplitudes.
2. To calculate each vertex amplitude numerically as a complex number.
3. To reconstruct of them with the polarization sum, and calculate the helicity amplitudes numerically.

The merit of this method is that the extension of the package is easy, and that each vertex can be defined only by the type of concerned particles.

Here we adopt an algorithm in Ref. 10 and 11 for the implementation of the embedding Majorana fermions in CHANEL as follows:

- **policy**

1. To calculate a helicity amplitude numerically.
2. To replace each propagator by wave functions or polarization vectors, and calculate vertex amplitudes.
3. **Not to** move charge-conjugation matrices.

- **method**

1. To choose a direction on a fermion line.
2. To put wave functions, vertices and propagators along the direction in such a way:
 - i) To take the transpose for the reverse direction of fermions
 - ii) To use the propagator with the charge-conjugation matrix for the Majorana-flipped one.

As a result, the kinds of the Dirac-Majorana-scalar vertices are limited to four types:

$$J_{1\ h_1 h_2}^{[S]\rho_1 \rho_2} = \bar{U}^{\rho_1}(h_1, p_1, m_1) \Gamma U^{\rho_2}(h_2, p_2, m_2) \ , \quad (1)$$

$$J_{2\ h_1 h_2}^{[S]\rho_1 \rho_2} = U^{\rho_1 T}(h_1, p_1, m_1) \Gamma \bar{U}^{\rho_2 T}(h_2, p_2, m_2) \ , \quad (2)$$

$$J_{3\ h_1 h_2}^{[S]\rho_1 \rho_2} = \bar{U}^{\rho_1}(h_1, p_1, m_1) C^T \Gamma^T \bar{U}^{\rho_2 T}(h_2, p_2, m_2) \ , \quad (3)$$

$$J_{4\ h_1 h_2}^{[S]\rho_1 \rho_2} = U^{\rho_1 T}(h_1, p_1, m_1) \Gamma^T C^{-1} U^{\rho_2}(h_2, p_2, m_2) \ , \quad (4)$$

where U 's denote wave functions, and C is the charge-conjugation matrix. The symbol Γ stands for the scalar vertex such as

$$\Gamma = A_L \cdot \frac{1 - \gamma}{2} + A_R \cdot \frac{1 + \gamma}{2} \ .$$

The vertices $J_2^{[S]} \sim J_4^{[S]}$ are related to the vertex $J_1^{[S]}$ which has been already defined as the Dirac-Dirac-scalar vertex in the subroutine FFS of CHANEL. The relations among the vertices are as follows:

$$J_{1\ h_1 h_2}^{[S]\rho_1 \rho_2} \rightarrow \text{FFS} \ , \quad (5)$$

$$J_{2\ h_1 h_2}^{[S]\rho_1 \rho_2} = -J_{1\ h_1 h_2}^{[S]-\rho_1 -\rho_2} \rightarrow \text{FFST} \ , \quad (6)$$

$$J_{3\ h_1 h_2}^{[S]\rho_1 \rho_2} = -J_{1\ h_1 h_2}^{[S]\rho_1 -\rho_2} \rightarrow \text{FFCS} \ , \quad (7)$$

$$J_{4\ h_1 h_2}^{[S]\rho_1 \rho_2} = -J_{1\ h_1 h_2}^{[S]-\rho_1 \rho_2} \rightarrow \text{FFSC} \ , \quad (8)$$

Thus we have built three new subroutines FFST, FFCS and FFSC. We have performed the installation of the subroutines above with the interface on the new GRACE system.

3. Tests for the system

At the start for the check of our system, we have written the model file of SUSY QED. In this case, there is only one Majorana fermion, photino. Next we have extended the model file and the definition file of couplings for the MSSM. The tests have been performed by the exact calculations with the two methods, our system and REDUCE, in such a manner:

1. To calculate the differential cross-sections at a point of the phase space in the two methods with GRACE and REDUCE.
2. To calculate the differential cross-sections over the phase space with REDUCE.
3. To integrate the differential cross-sections over the phase space in the two methods with GRACE and REDUCE.

With the GRACE system, we can get the differential cross-sections and the scattered plots by one time of the integration step with BASES. For writing REDUCE sources, we use the different method to treat Majorana fermions in Ref. 15. In Table I, the tested processes are shown as a list.

Table 1. The list of the tested processes.

Process		Number of diagrams	Comment	Check
SUSY QED				
$e^-e^- \rightarrow$	$\tilde{e}_R^- \tilde{e}_R^-$	2	Majorana-flip	OK
	$\tilde{e}_L^- \tilde{e}_L^-$	2	in internal lines	OK
	$\tilde{e}_R^- \tilde{e}_L^-$	2		OK
$e^-e^+ \rightarrow$	$\tilde{e}_R^- \tilde{e}_R^+$	2	Including pair	OK
	$\tilde{e}_L^- \tilde{e}_L^+$	2	annihilation	OK
$e^-e^+ \rightarrow$	$\tilde{e}_R^- \tilde{e}_L^+$	1	Values are	OK
	$\tilde{e}_R^+ \tilde{e}_L^-$	1	equal	OK
$e^-e^+ \rightarrow$	$\tilde{\gamma} \tilde{\gamma}$	4	F-B symmetric	OK
$e^-e^+ \rightarrow$	$\tilde{\gamma} \tilde{\gamma} \gamma$	12	Final 3-body	OK
$e^-e^+ \rightarrow$	$\tilde{e}_R^- \tilde{\gamma} e^+$	12	Everything for tests	OK
MSSM				
$e^-e^- \rightarrow$	$\tilde{e}_L^- \tilde{e}_L^-$	8	4 Majorana fermions	OK
$e^-e^+ \rightarrow$	$\tilde{\chi}_1^- \tilde{\chi}_1^+$	3		OK
$e^-e^+ \rightarrow$	$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma$	14	Final 3-body	OK

For an example of the tests, we present the results for the process of the single-selectron production, $e^-e^+ \rightarrow \tilde{e}_R^- \tilde{\gamma} e^+$ within SUSY QED. In this process, there exist diagrams with Majorana-flips in internal and external lines, and ones with one-photon exchange in s-channel and t-channel.¹⁶ Thus this is the most important process for the test of our system. In Fig. 1, we show the angular distribution of the outgoing positron in this process. Here we use BASES for the calculation from the REDUCE output. The result is in beautiful agreement with the value that is obtained by GRACE at each bin of the histograms. Since the two diagrams with the one-photon exchange dominate in this case, there is a steep peak in the

Fig. 1. Angular distribution of the positron in $e^-e^+ \rightarrow \tilde{e}_R^- \tilde{\gamma} e^+$.

direction of the initial positron. In such a case, the equivalent-photon approximation (EPA) works well.¹⁷ The comparison between the results of the exact calculation and those of EPA is shown in Ref. 18. In the experiment, the single-photon event from $e^-e^+ \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma$ is important for the search of SUSY particles. We have also calculated this process with our system.¹⁹

4. Summary

We introduce a new method to treat Majorana fermions on the GRACE system for the automatic computation of the matrix elements for the processes of the SUSY models. In the first instance, we have constructed the system for the processes of the SUSY QED because we should test our algorithm for the simplest case. Next we have extended the model file and the definition file of couplings for the MSSM. The numerical results convince us that our algorithm is correct. It is remarkable that our system is also applicable to another model including Majorana fermions.

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